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Photonic Integrated Circuit Comprising Mode-Locked Laser and Pulse Interleaver for Wavelength Tunable THz Signal Generation

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***Abstract*—We report a photonic chip comprising multiple colliding pulse mode-locked laser and delay line-assisted Mach-Zehnder interleaver to generate 350GHz wave signal. With this mode-locked laser fourth harmonics are obtained. The interleaver quadruples the repetition rate. An integrated phase modulator enables wavelength tuning up to 0.03nm.**

Keywords—mode-locked laser; Mach-Zehnder interferometer; tunable laser; photonic integrated circuit; microwave photonic; Terahertz

I. Introduction

Mode-locked lasers generating ultrafast optical pulse train and frequency comb within the millimeter wave region (mmW, 30 – 300 GHz) and Terahertz (THz, 0.1 – 10 THz) are of interest in a range of applications including microwave photonics [1]. Owing to its small footprint, low power consumption, improved alignment and immunity to vibration, mode-locked lasers in the form of photonic integrated circuits are highly desirable for realizing compact devices [2].

Generally, the repetition rate of mode-locked laser is inversely proportional to the cavity length. For achieving an extremely high repetition rate, the corresponding short cavity usually limits its capability to accommodate gain sections. Therefore, schemes to increase the repetition without sacrificing cavity length must be applied.

As recently reported [3], on-chip multiple colliding pulse mode-locked laser (mCPML) is a promising candidate for such an issue. In a mCPML, the cavity has been divided into sub-cavities that maintain a certain length proportion to the whole cavity. Two counter propagating pulses circulate in the sub-cavities divided by absorbers and collide with each other at absorbers, thus producing a train of short pulses at a repetition rate that is a multiple of the cavity mode space frequency defined by the two end mirrors.

On the other hand, the pulse train can be further processed after being delivered from the mode locked laser cavity through the transmission port of mirror. Since the pulses in train are usually short (< 2 ps) with respect to the pulse repetition period (e.g., 25 ps, for a 40 GHz pulse train) interleaving pulses is able to increase the temporal capacity. The structure to interleave pulses is based on asymmetric Mach-Zehnder interferemeter (MZI) with precisely set delay line to double the repetition rate [4].

This pulse interleaver is not only a repetition rate multiplier but also a MZI filter. Similarly, the mode-locked laser emits a pulse train in the time domain which is actually a comb in the frequency domain. To combine a mode locked laser with such a pulse interleaver, the spectral interplay should be taken into account; the frequency comb lines should always be aligned to the passband of filter, implying a wavelength tuning mechanism is essential for implementing this combination.

In this paper, we present a monolithic THz signal generator by using a mCPML followed by a delay line-assisted Mach-Zehnder interleaver as demonstrated in Fig. 1. In such a mCPML depicted, the fourth harmonic is obtained so that the repetition rate (80 GHz) is four times the cavity mode space frequency (20 GHz). An electro-optic phase modulator (EOPM) has been deployed in the mode-locked laser to adjust the wavelength of comb lines to fit into filter's passband.

The delay line-assisted Mach-Zehnder interleaver post processing is consisted of two stages of asymmetric Mach-Zehnder interferometers, in which optical delay lines corresponding to half and quarter of pulse train's period are arranged, respectively. Each stage of delay line-assisted Mach-Zehnder interleaver allows repetition rate doubling. Consequently, at the end output port of post processing the repetition rate quadrupling is achieved. The interleaver pushes the repetition rate from 80 GHz up to higher than 300 GHz.

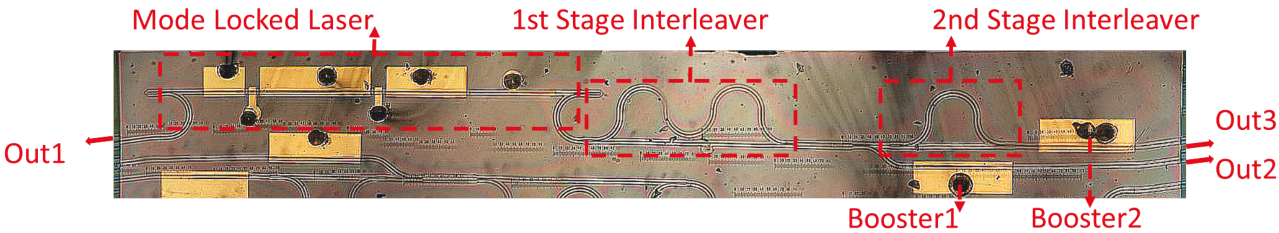

Fig. 1. Microscope photograph of the proposed device

II. Device Description

A. Multiple colliding pulse mode-locked laser with EOPM

The mCPML structure is depicted in Fig. 2, featuring a couple of saturable absorbers (SAs) and semiconductor optical amplifiers (SOAs) arranged precisely along the cavity. At each SA, two counter-propagating pulses arrive coherently and thus produce sharpened pulses.

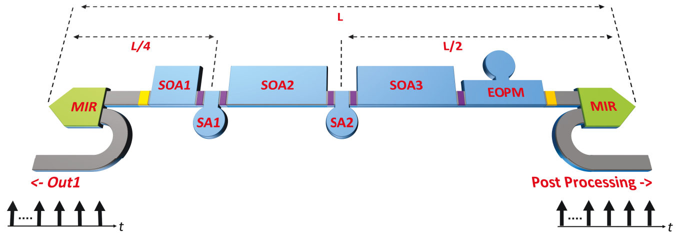

Fig. 2. Schematic diagram of multiple pulse colliding mode locked laser with EOPM

The total cavity length denoted as L is about 2 mm long corresponding to a repetition rate of 20 GHz, terminated at a pair of 2-port MIRs (2xMIRs) providing 50% reflectivity. A saturable absorber (SA2) is placed at the midpoint of the cavity. An SA is exactly the same as an SOA except that an SA is reverse biased while an SOA is forward biased. We have placed another SA (SA1) at quarter cavity length from the left MIR end. This arrangement quadruples the frequency, increasing the repetition rate to 20 GHz x 4 = 80 GHz. Three SOAs of different lengths are distributed to provide optical amplification in these sub-cavities that are divided by SAs. Finally, an electro-optic phase modulator (EOPM) is situated beside SOA3 for wavelength tuning. All active pads are wire bonded to metal tracks rather than directly probing. SOAs are driven with Thorlabs LDC8005 PRO8000 Laser Diode Current Control Modules whilst SAs and EOPM are reverse-biased with Agilent E3631A Triple Output Power Supply. The biasing condition is as follows: SOA1: 9.2 mA, SA1: 0.7 V, SOA2+SOA3: 89 mA, SA2: 2.0 V.

All these active sections are based on the same InGaAsP multi-quantum well core. The chip, fabricated in an active-passive integration technology allows us to use passive waveguides to maintain the optimum SOA to SA length ratio of 20:1 and sub-cavity length ratio of 1:1:2. Besides, isolation sections are inserted between adjacent active components to prevent unwanted current flow. Active and passive waveguides are bridged via transition sections. The use of 2xMIR mirrors do not only reflect light waves but also transmit the optical pulse train through the other port for measurement or further on-chip optical signal processing. At the left end of circuit (Out1) the laser beam is then coupled into a lensed fiber connected to Yokogawa AQ6370B Optical Spectrum Analyzer. At the right end port the identical laser beam is passing for its post processing.

B. Delay line-assisted Mach-Zehnder interleaver

In order to further increase the repetition rate, an optical clock multiplier is used. The on-chip rate multiplier is illustrated in Fig. 3 which is based on time division multiplexing configuration. The pulse interleaver is made up of two stages of asymmetric Mach-Zehnder interferometers. In each stage, a coupler splits the incoming pulse train in two beams. These two separated optical beams propagate along the corresponding optical arm of Mach-Zehnder interferometer. The Mach-Zehnder interferometer is asymmetric that one arm is with an additional delay line while the other is not. These two beams experiencing different time delay recombine at the combiner forming a pulse train with a doubled repetition rate. The splitter and combiner are implemented by using multimode interference coupler (MMI). The delay line arrangement is realized by using straight and curved passive waveguides with accurately set path length.

In 1st stage interleaver the physical length of optical delay line is 540 um while that in 2nd stage interleaver is 270 um so that τ_1 and τ_2 are half and quarter of repetition period of 80 GHz. The beam processed via 1st stage interleaver propagates through semiconductor amplifier Booster1. The beam processed via both 1st and 2nd stage interleaver propagates through semiconductor amplifier Booster2. Hence a processed pulse train with a doubled repetition rate achieved after Booster1, and a quadrupled repetition rate achieved after Booster2. These beams can be coupled into lense fiber from waveguide outputs (Out2 and Out3). This entire circuit contains five SOAs, two SAs, two MIRs, several MMIs as well as passive components. The chip was fabricated in a multi-project wafer (MPW) run by SMART Photonics' foundry service, through JePPIX (Joint European Platform for InP-based Photonic Integrated Components and Circuits) [5].

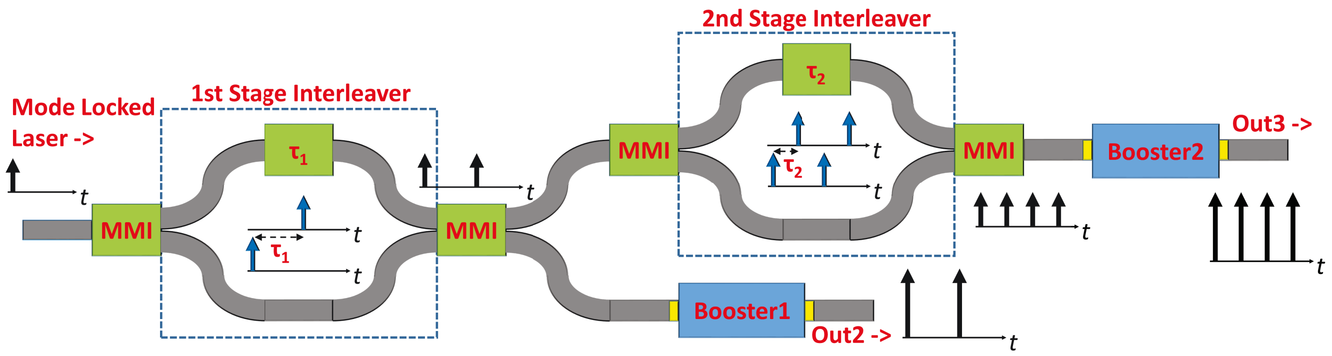

Fig. 3. Schematic diagram of post processing: Delay line-assisted Mach-Zehnder interleaver

III. RESULT & DISCUSSION

As presented in Fig. 4, the spectrum of multiple colliding pulse mode locked laser is shown with reverse bias voltage of EOPM V_{EOPM} of 0, 2, and 4 V, respectively. Focusing on the spectrum with V_{EOPM} = 0 V, it resembles a typical optical frequency comb generated by mode-locked laser where the dominant modes are evenly distributed (marked with a to f). Aside from the six dominant modes, there are other lower modes whose power is below -50 dBm. The fixed wavelength offset between them is 0.16 nm (~20 GHz) and the six dominant lines are situated about 0.65 nm (~80 GHz) apart. Notice that in this spectrum three modes are suppressed out of every four modes. This agrees with the arrangement in the aforementioned design of mCPML in which fourth harmonic components are to be obtained. The side mode suppression ratio is around 30 dB.

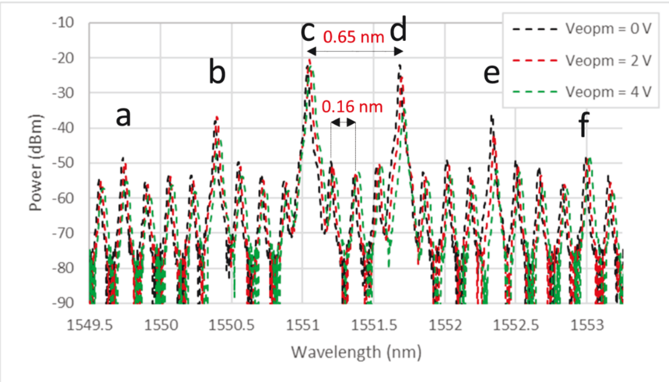

Fig. 4. Spectrum at Out1 with reverse bias voltage V_{EOPM} = 0, 2, and 4 V

V_{EOPM} has an influence on the spectrum. Comparing the spectrum with V_{EOPM} varied from 0 to 4 V, we see that as V_{EOPM} increases the spectrum shifts to the right. The spectrum with V_{EOPM} of 0, 2, and 4 V are similar that 0.65 nm (~ 80 GHz) offset is always maintained. To study the dependency, the wavelength shift and free spectral range (FSR) versus V_{EOPM} are plotted in Fig. 5. Within the range of V_{EOPM} (0 to 4 V) the free spectral range is always around 0.65 nm which means the repetition rate of this mode locked laser is fixed, at around 80 GHz. The wavelength shift goes ups and downs in a rising trend. When the EOPM is reverse-biased at 4V, there is a wavelength shift of 0.03 nm which is corresponding to a frequency shift of 3.75 GHz. The nonlinear movement around V_{EOPM} = 3 V is not clear and needs further investigation.

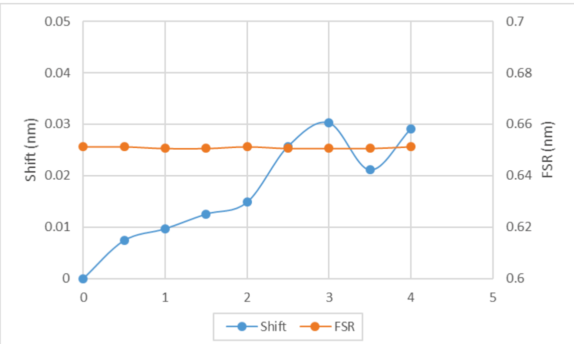

Fig. 5. Wavelengh shift and free spectral range at Out1 as function of V_{EOPM}

The spectrum at Out3 is presented in Fig. 6. As a result of frequency quadrupling by the cascaded MZI interleaver, the spectral offset between dominant modes (a and b) should be four times the offset in Fig. 4. However, the spectral offset in Fig. 6 is 2.78 nm, even longer than expected (2.60 nm). 2.78 nm band is equal to 350 GHz. The offset between lower lasing modes is still 0.16 nm, same as Fig. 4. At V_{EOPM} = 0 V, it has a side mode suppression ratio of around 25 dB.

It should be highlighted that in Fig. 6, the wavy baseline is introduced by the cascaded MZI filter which is absent in Fig. 4. The filter enhances the side mode suppression ratio if modes of interest are situated in the passband. As we see the dominant mode b is not perfectly positioned; it should appear at the center of passband. However, with V_{EOPM} below 4 V the EOPM designed for this purpose does not have a sufficient tuning ability.

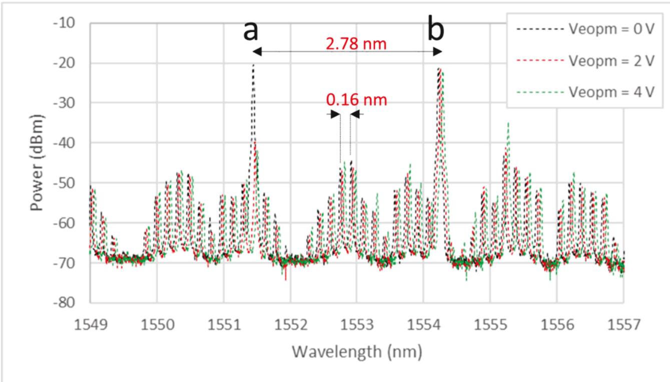

Fig. 6. Spectrum at Out3 with reverse bias voltage V_{EOPM} = 0, 2, and 4 V

As V_{EOPM} increases, the modes shift to the right but the wavelength offset is invariant as shown in Fig. 7. A wavelength shift of 0.06 nm corresponding to 7.5 GHz at most can be achieved by adjusting V_{EOPM} up to 4 V. The free spectral range is always 2.78 nm with negligible variation.

In addition to frequency movement, power of dominant modes is affected by V_{EOPM}. In Fig. 8, the peak power of two dominant modes (a and b) is presented as function of V_{EOPM}. Varying V_{EOPM} from 0 to 4 V, the power of mode b keeps around -22 dBm but the power of mode a drops down drastically when $V_{EOPM} > 1$ V. This behavior limits the available tuning range to $V_{EOPM} < 1$ V; when $V_{EOPM} > 1$ V, mode b gets dominant over mode a, forming a single mode operation.

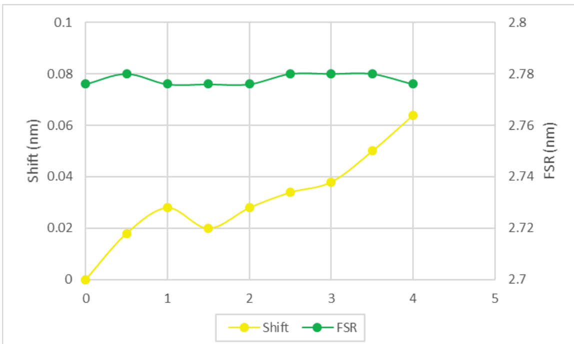

Fig. 7. Wavelengh shift and free spectral range at Out3 as function of V_{EOPM}

This unequal impact may indicate that mode locking does not occur any longer if $V_{EOPM} > 1$ V; by tuning V_{EOPM} the effective optical path length in cavity is changed accordingly, and the sub-cavity length ratio may deviate too far from 1:1:2. As a conclusion, this wavelength tuning is available only if $V_{EOPM} < 1$ V, with a maximum shift of wavelength of 0.03 nm.

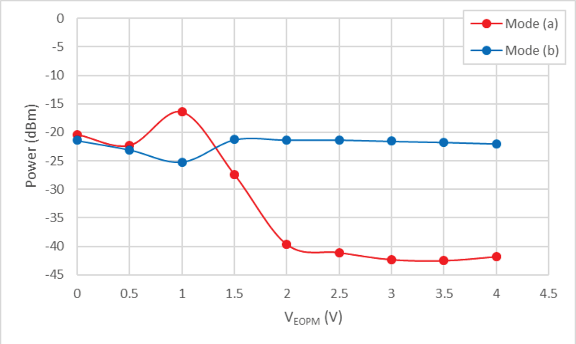

Fig. 8. Power of two dominant modes at Out3 as function of V_{EOPM}

IV. Conclusion

In this paper, we have demonstrated a monolithic 350 GHz signal generator by combining a mCPML with a post processing delay line-assisted Mach-Zehnder interleaver. The mCPML emits a pulse train of 80 GHz which is four times the cavity mode space frequency 20 GHz. The delay line-assister Mach-Zehnder interleaver comprises two stages of asymmetric Mach-Zehnder interferemeters thus quadrupling the repetition rate. Considering the spectral interplay, this device features wavelength tuning by inserting a phase modulator for adjusting the mode-locked laser to coordinate with the cascaded MZI filter.

By showing the spectrum of such a signal generator, its capability to generate THz signal is proven. However, although the wavelength tuning does work its capacity is still insufficient (0.03 nm) due to unequal impact on power of dominant modes; it is basically a contradiction to sustain the certain ratio of sub-cavities to have modes locked, with the optical phase being adjusted simultaneously. Eventually, according to the lesson learned from this work, to achieve wavelength tuning and high repetition rate at the same time, a couple of phase modulators deployed in a symmetric colliding pulse mode locked laser would be preferable over a multiple colliding pulse mode locked laser with one phase modulator.

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